Investigations of Light Scattering by Ocean Waters

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LONG-TERM GOALS

Our overall, long-term goal is to significantly advance our understanding of the light scattering properties of marine particles as well as their general optical properties. Our goal is to study particle optical properties using a unique set of new optical instruments that we have developed on previous ONR funded projects. Observational studies will be conducted at sea in various coastal waters, and careful laboratory experiments of particle optical properties will be performed.

OBJECTIVES

All of the instruments required for us to carry out a thorough investigation of light scattering by marine particles, both in situ and benchtop, are now in our possession, having been developed on a previous ONR funded project (see the annual report, "Light Scattering Properties and Processes of Coastal Waters). We thus propose to address the following major questions in this research program. We expect, of course, that new or related questions will arise in the course of this research and will be addressed as needed. Accordingly, the basic objectives, or problems we seek to address are:

1. What is the range of variability in the shape of the VSF (i.e., the scattering phase function) for oceanic waters, especially coastal waters? How does the phase function relate to other optical property measurements, the nature of the particles, and biological properties such as chlorophyll concentration? And most basically, what are the phase functions for the various endmember classes of marine particles (e.g., phytoplankton, organic and inorganic detritus, sediments, etc.)?

2. How accurate and robust is the conversion to estimate the backscattering coefficient from a measurement of the VSF at a nominal angle in the backward direction? In other words, how variable is χ in the equation $b_b = 2\pi\chi\beta(\psi_0)$, where $\beta(\psi_0)$ is the nominal-angle measurement of the VSF (for the HydroScat, ψ_0 = 140 degrees)?

3. How well can Mie theory be used to calculate the VSF of marine particles based on their measured size distributions with a Coulter Counter? Does the estimated complex index of refraction for obtaining the best match with VSF measurements match the refractive index inferred from that traditional approach of using spectral absorption and beam attenuation measurements (e.g., *Bricaud, Morel and Prieur* [1983])?

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14. ABSTRACT

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15. SUBJECT TERMS

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4. What are the particles and processes responsible for the shapes and magnitudes of the VSF? For example: Is turbulence responsible for the slope of the VSF near 0 degrees? Are submicron particles the chief source of optical backscattering? Does near-forward scattering depend chiefly on the particle size, as opposed to their shape and/or refractive index?

5. In terms of instrument closure, how consistent are comparisons of various optical properties measured with different instruments and methods? What are the greatest sources of errors and how can they be improved? In terms of model closure, how well do radiative transfer calculations actually match measured AOP's when using measured IOP's as input? Again, what are the greatest sources of errors under various conditions and how can they be improved? In terms of inverse problems, how does the measured VSF, vis a vis measurements of concomitant optical properties, affect inverse relationships such as those between IOP's and AOP's?.

APPROACH

We have been and continue to carry out an extensive program of both field and laboratory research on the nature of light scattering by ocean waters and their constituent particles. This research is unprecedented in its scope, as we seek to address the outstanding questions about light scattering by marine particles as described in our Objectives above. Nearly all of the instruments, equipment and facilities to conduct this research program have already been developed at HOBI Labs. These include the HydroBeta, HydroScat-6, HydroScat-2, a-beta, c-beta, HydroRad and HydroDAS. Other commercial instrumentation that we have and will use in our research on this project include a Coulter Counter, spectrophotometer, PRR600, AC9, and CTD.

HydroBeta is unique among all ocean-optical instruments ever developed and incorporates many impressive capabilities important to gaining a more complete understanding of the VSF of ocean waters. This instrument is designed to measure the VSF at 11 angles *simultaneously* of ambient, *undisturbed* water. What's more, these angles can be set to any 11 angles in the range from 5 to 170 degrees in five-degree increments. With a sampling rate of 1 Hz, the HydroBeta is easily used as a profiling instrument, allowing us to investigate the variability of the VSF throughout the water column concomitant with a full range of optical and physical water-property measurements.

Successfully developing a multi-angle VSF instrument is only the first, though quite difficult step in measuring the VSF of ocean waters. The next, though equally important step is the accurate calibration of the instrument. This latter step historically has been a controversial and unresolved issue, bringing into question all previously reported VSF measurements. Petzold, for example, used a purely analytical calibration technique that he himself acknowledged in his famous 1972 report contained many unresolved questions. More recent VSF makers and users of VSF instruments have attempted to use spherical particles and Mie theory calculations of the VSF to calibrate their measurements. The problems with this approach are myriad and this approach is far from being proven or accepted. We have developed a method for calibrating HydroBeta with a method that relies only on the Lambertian properties of a diffusely reflecting target. Errors in the Lambertian target assumption are at most a few percent. The method is similar to the thoroughly documented and well tested technique we developed for calibrating the HydroScat backscattering instruments [Maffione and Dana, 1997]. This method involves measuring each receivers response to a Lambertian target, illuminated by the instrument's light source, over the receivers complete field-of-view. The result is a complete, absolute, in-water calibration that involves a bare minimum of assumptions, all of which can be independently verified.

WORK COMPLETED

We have just completed the first year of this program during which we conducted five extensive cruises in Monterey Bay, covering the full seasonal variations in this region. Data have not been submitted to a national archive, but we are making data available via our website. To achieve our research goals, we developed an integrated profiling system called HydroProfiler. This package incorporates numerous optical and other oceanographic instruments that are integrated into a highly sophisticated multi-instrument data integration system called HydroDAS developed by HOBI Labs. A picture of the HydroProfiler aboard the R/V Pt. Sur is shown in Figure 1. In addition to our five ocean cruises, we conducted extensive laboratory measurements of various mixtures of spherical particles to investigate and demonstrate the calibration accuracy of our scattering instruments. We also conducted laboratory measurements of air bubble distributions. We presented two papers and two posters at the last Ocean Sciences meeting on our research on scattering.

RESULTS

The HydroBeta is the first in-situ instrument that measures the VSF at multiple angles simultaneously in undisturbed water (i.e., it is not a flow through system). Because the sampling rate is 1 Hz, this instrument is well suited for mounting on profiling packages. Figure 2 shows an example profile in Monterey Bay, illustrating the depth profile of 12 angles of the VSF. Figure 3 shows the VSF vs. scattering angle at selected depths from the profile in Figure 2. One exciting thing to point out about this plot is that in a single profile, we obtained more data on the VSF than was published in the seminal report by Petzold (1972). Moreover, the vertical variability in the particle distributions, common to Monterey Bay, allowed us to obtain, in a single profile, measurements of the VSF that cover the full range of VSF's published by Petzold, from clear oceanic waters to turbid near-shore waters. Considering the number of profiles obtained in a single cruise, we are rapidly expanding our knowledge of the VSF of ocean waters, which was a virtual desert over the past 30 years.

One of the many problems in ocean optics that our measurements are allowing us to investigate is the effect of the shape variability in the VSF on estimating the backward scattering coefficient from a single measurement of the VSF (Maffione and Dana, 1997, 2002). Our original conjecture, based on Mie calculations, was that a single measurement of the VSF anywhere in the range from 120 to 140 degrees could be used to estimate the backward scattering coefficient with an error of 10% or less. The results shown in Figure 4 confirm this conjecture from actual measurements of the VSF made with the HydroBeta. Moreover, it appears to show that "best" angle for this determination is around 135 degrees, the angle at which the HydroScat measures the VSF to estimate the backward scattering coefficient (Maffione and Dana, 1997). Another problem we're investigating with our VSF measurements is how best to invert these measurements to obtain information on the nature and distribution of suspended particles (Maffione, 2002). Figure 5 shows a graph of the particle size distribution, in absolute magnitude, as estimated from our algorithm for inverting the VSF. We are pursuing a number of other problems that space does not allow us to expand on here.

IMPACT/APPLICATIONS

We expect that our measurements of the complete VSF will have an enormous impact on nearly all areas of optical oceanography. No measurements of the kind we plan to obtain have ever been made. Indeed, the nearest data of this type were obtained over 25 years ago. This lack of systematic and complete VSF measurements has greatly hampered our understanding of light scattering by marine particles, the testing and refinement of optical models, and the calibration of ocean-optical systems. Our extensive collection of optical property measurements in various coastal environments will be a critical aid in developing bio-geo-optical models of coastal waters.

TRANSITIONS

Our results, especially the VSF measurements, are being utilized by others in optical modeling and radiative transfer efforts in the investigation of remote sensing, underwater visibility and ocean lidar.

RELATED PROJECTS

The research we are conducting on this project is closely related to the research we are conducting on two ONR DRI's, CoBOP and HyCODE. Both of these DRI's benefit from, and contribute to this project. Our DRI projects also involved the study of water optical properties and their effect on radiative transfer. We anticipate that work being conducted at NRL-Stennis by Dr.'s Robert Arnone and Alan Weidemann will also benefit from our research. Our VSF measurements are also being used by groups doing optical modeling of ocean lidar.

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Maffione, R.A., and D.R. Dana, 2002. Measurements of the volume scattering function of ocean waters and implications of its variability, *J. Geophys. Res.* (submitted).

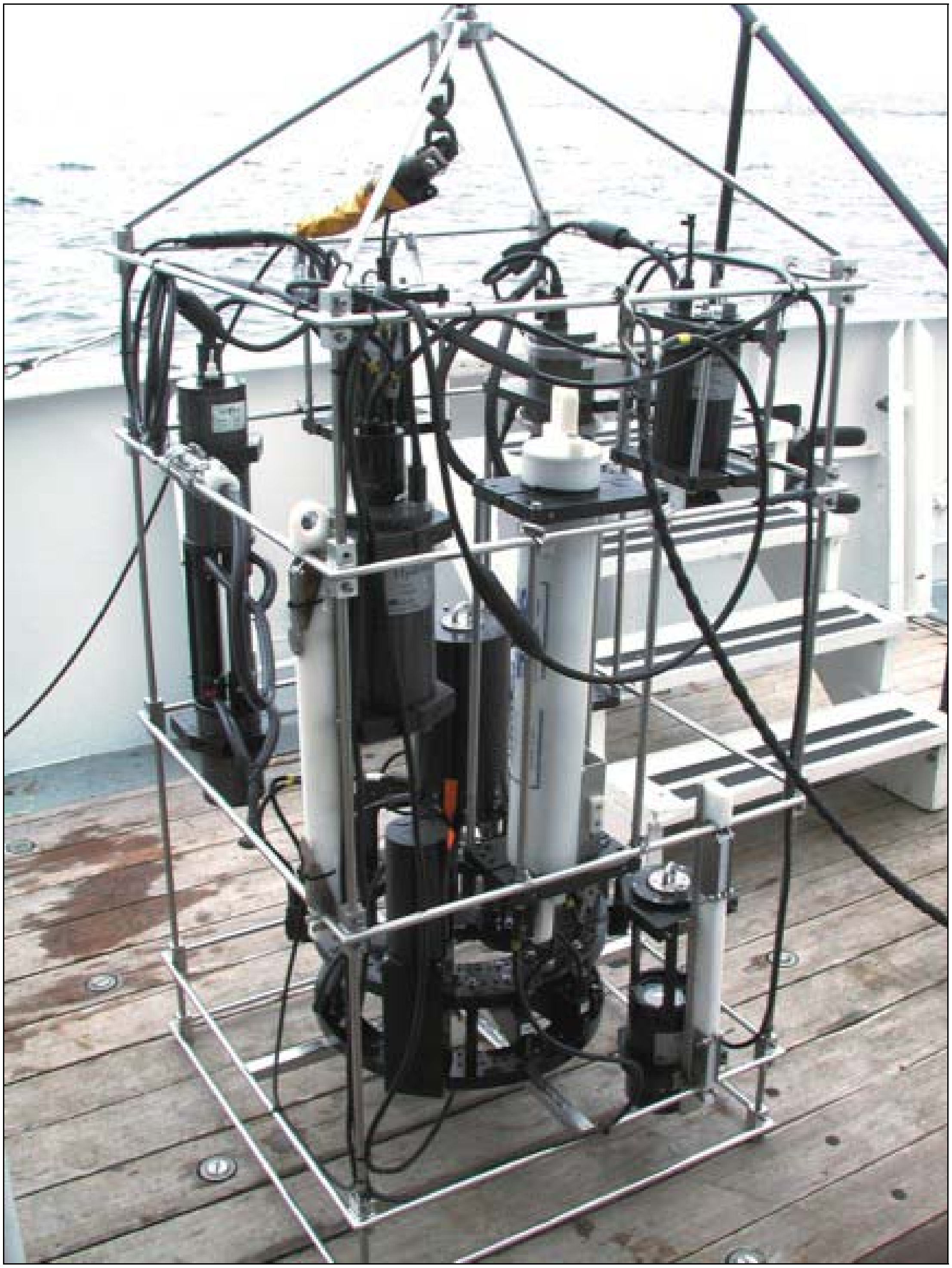

Figure 1. Photograph of the HydroProfiler aboard the R/V Pt. Sur. Instruments on this package include the HydroBeta, a-beta, c-beta, two HydroScat-2's, two AC9's, and a Seabird CTD. All instruments are integrated into a HydroDAS, a multi-instrument data integration system that collects data from all instruments and sends it up a two-conductor cable in real time while also supplying power to all the instruments.

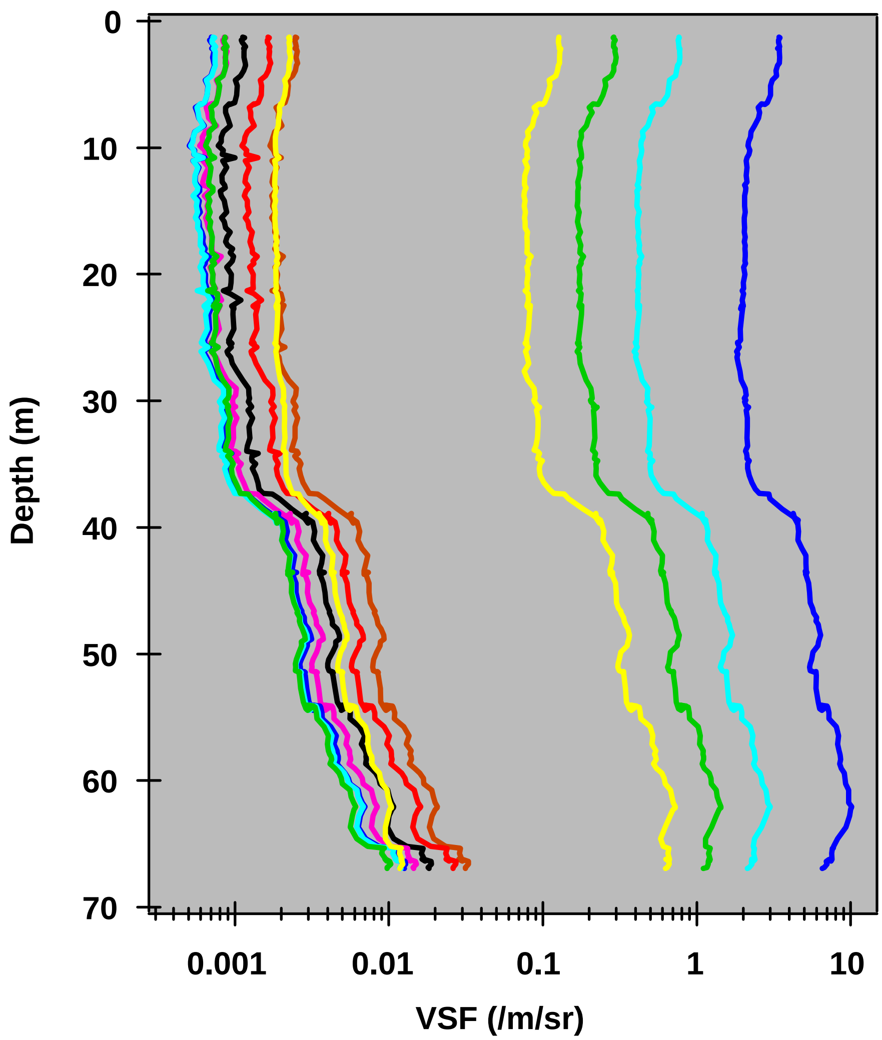

Figure 2. Graph of a depth profile of the VSF at 12 angles, all measured simultaneously at a sampling rate of 1 Hz.

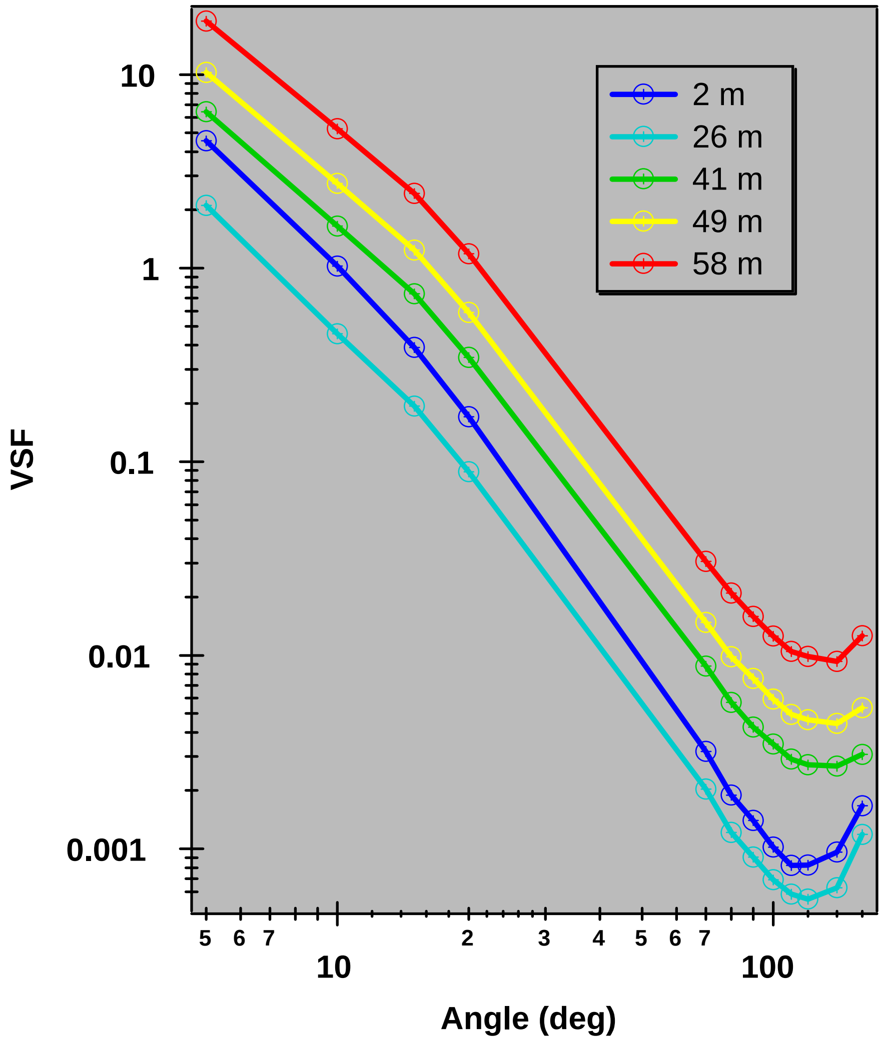

Figure 3. Graph of the VSF vs. scattering angle at selected depths from the profile shown in Figure 2. Note the significant difference in magnitude and shape of the VSF, especially in the back hemisphere, due to changes in the types of particles between the surface layer and interior.

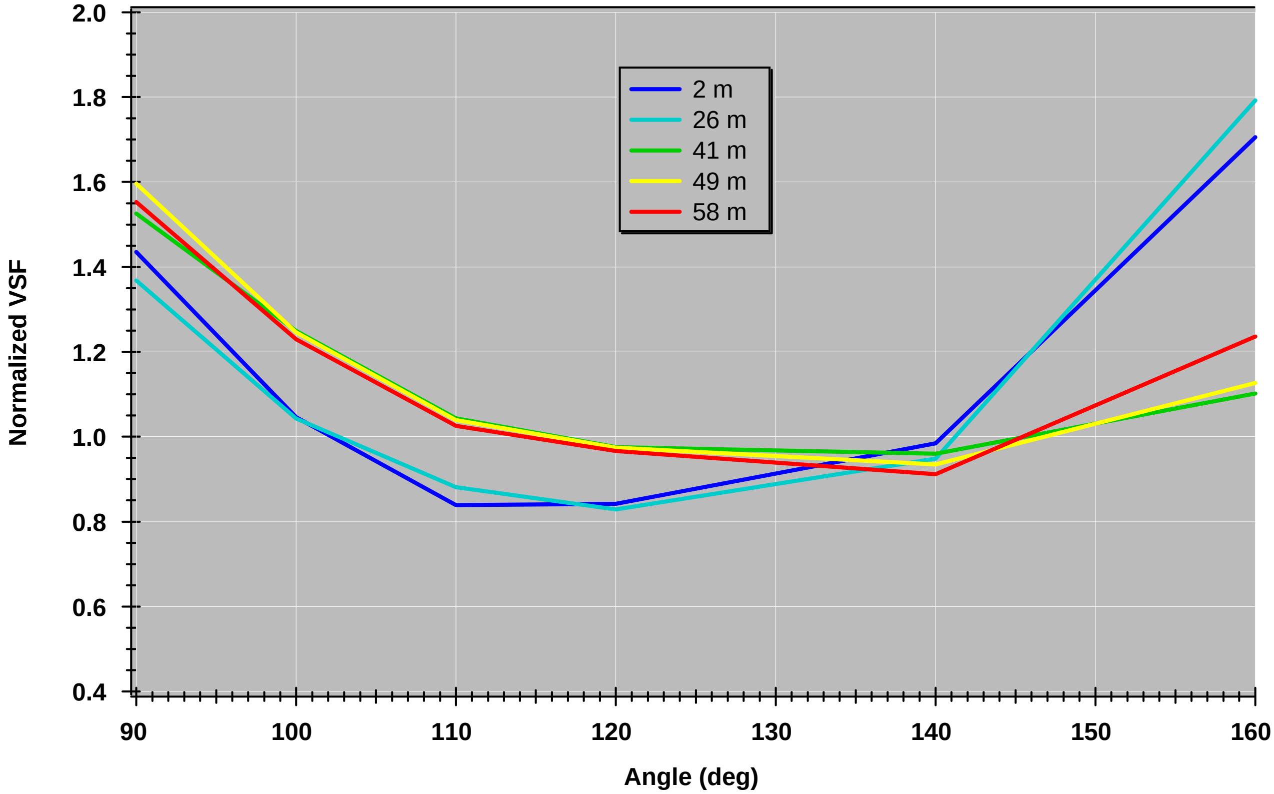

Figure 4. Graph of the normalized VSF in the backward hemisphere as measured by the HydroBeta. Data are from Figure 3. This plot illustrates the variation of the shape of the VSF in the back hemisphere for the purposes of estimating the backward scattering coefficient from a single measurement of the VSF.

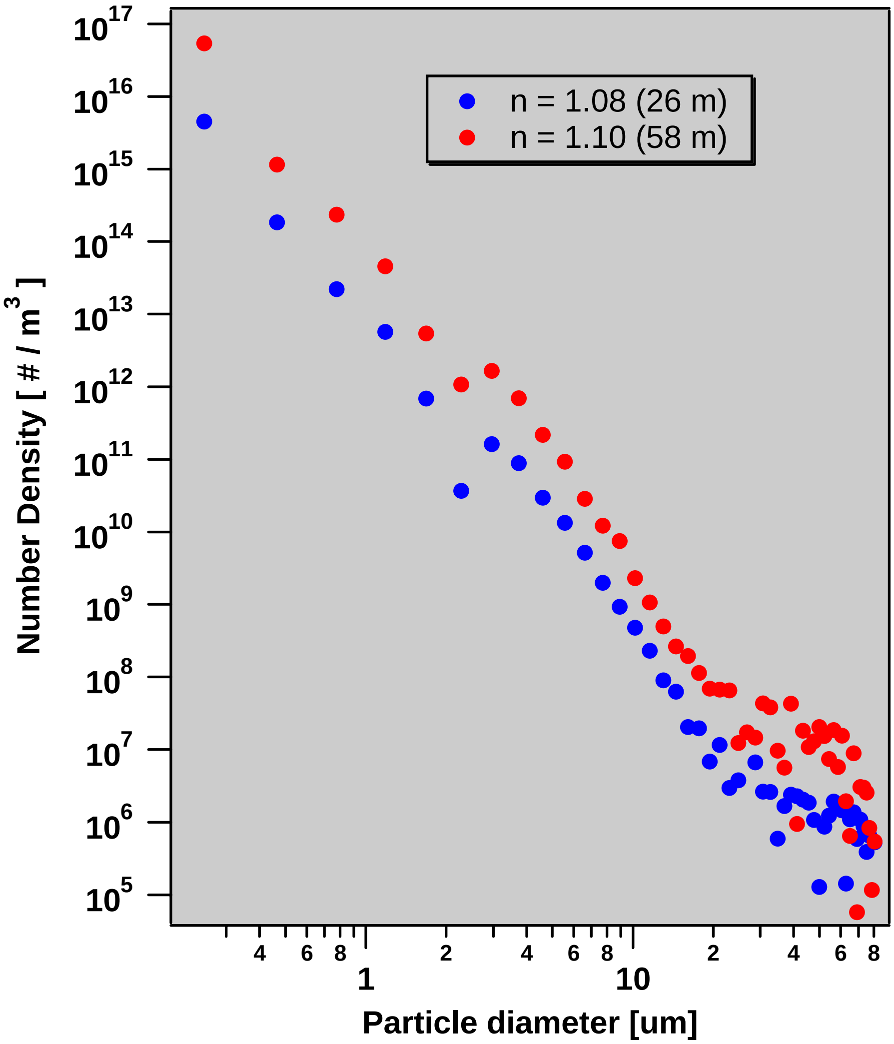

Figure 5. Graph of the retrieved particle size distribution from measurements of the VSF made with the HydroBeta.